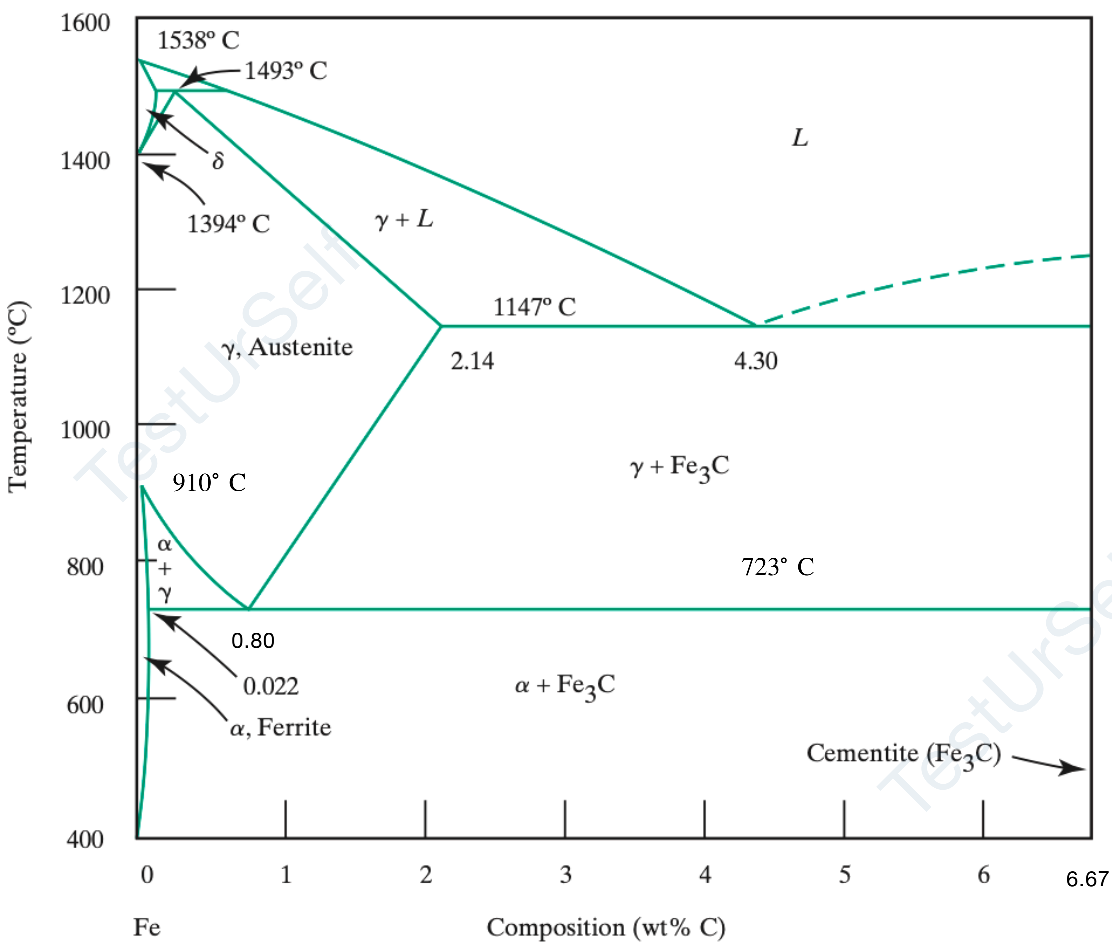
Notes on

# $Fe\text{-}Fe_3C$ diagram

Imagine this diagram as a **"recipe book"** for making different types of steel and cast iron.

It shows how iron and carbon behave at different temperatures and carbon levels.

Iron-Iron Carbide $(Fe\text{-}Fe_3C)$ or Iron - Carbon $(Fe\text{-}C)$ Phase Diagram helps us understand the different forms that steel and cast iron can take, which are made up of iron and carbon, along with some other elements in small amounts.



Iron-iron carbide phase diagram is like a map that shows us what happens to iron as we heat it up (on the vertical axis) and add more carbon (on the horizontal axis). At the start, when there's only a tiny bit of carbon (less than $0.008\,\%$), iron behaves just like pure iron because the carbon is more of an impurity than an actual part of the metal. But as we add more carbon, iron begins to mix with it and form what we call an alloy, until it reaches a point where it can't hold any more carbon.

In the diagram, we notice that when the carbon content reaches $6.67\,\%$, the iron undergoes a transformation into a compound called Cementite or Iron Carbide, which has a chemical formula of $Fe_3C$.

Cementite, however, is not stable over prolonged heating; it decomposes into iron and carbon. In practical terms, most cast irons and steels contain less than $6.70\,\%$ carbon by weight. Hence, it's ideal to focus solely on the $Fe - Fe_3C$ diagram, as $Fe_3C$ is a component of iron.

## Types of Phases in Iron Iron Carbide Phase Diagram:

Once we've grasped the fundamental concepts, we can identify several phases of iron highlighted in the phase diagram.

**$\alpha$-Ferrite**, or $\alpha$ iron, refers to the crystal structure of iron, specifically characterized by its Body Centered Cubic (BCC) arrangement at certain temperatures and compositions. Ferrite, which is a solid solution of carbon in $\alpha$-iron, is essentially another term for $\alpha$-ferrite. $\alpha$-iron remains stable within the temperature range from approximately -273°C to 910°C.

At 723°C, the maximum amount of carbon that can be dissolved in $\alpha$-ferrite is 0.025%. This solubility decreases as the temperature decreases until the carbon composition reaches 0.008% at 0°C. $\alpha$-Ferrite exhibits properties such as ductility, softness, and high magnetism. Its tensile strength is approximately 310 MPa, and its density is 7880 kg/m$^3$.

$\gamma$-Ferrite, or $\gamma$ iron, is associated with an iron crystal structure featuring Face Centered Cubic (FCC) arrangement. In an FCC structure, the crystal lattice comprises atoms positioned at each face and corner of the cube. $\gamma$-Fe is paramagnetic.

**Austenite**, a form of $\gamma$-iron, exists as a solid solution with an FCC structure and remains stable between temperatures ranging from 910°C to 1401°C. At 1130°C, the solubility of carbon in austenite is 2%, gradually decreasing to 0.8% at 723°C. Austenite shares similar characteristics with $\alpha$-ferrite, including ductility and softness, but it lacks ferromagnetism.

**Iron Carbide**, also known as Cementite ($Fe_3C$), has a crystal lattice where the number of iron atoms is three times greater than the number of carbon atoms. When carbon exceeds its solubility limit, iron transforms into iron carbide ($Fe_3C$). However, the solubility limit of carbon is relatively low, at $6.67\,\%$, with $93.3\,\%$ being iron. It shows **orthorhombic** crystal structure.

Iron carbide has a density of $7600\ \mathrm{kg/m^3}$ and is an intermetallic iron-carbon compound. It is characterized by being brittle and extremely hard. Iron carbide can exhibit magnetic properties at temperatures below $210^\circ\mathrm{C}$.

**$\delta$-Ferrite** occurs when, at $1394^\circ\mathrm{C}$, the Face Centered Cubic (FCC) structure of austenite changes to the Body Centered Cubic (BCC) structure known as $\delta$-ferrite. At $1493^\circ\mathrm{C}$, $\delta$-ferrite has a maximum solubility limit of carbon of $0.1\,\%$. Properties of $\delta$-ferrite include reduced fatigue and increased strength. It forms a solid solution with carbon at stable temperatures between $1401^\circ\mathrm{C}$ and $1539^\circ\mathrm{C}$. Beyond $1538^\circ\mathrm{C}$, iron reaches its melting point and undergoes melting.

## Boundaries in Fe-C diagram:

The boundaries within the Iron-Carbon (Fe-C) phase diagram delineate the limits of various phases and phase transformations that occur as a function of temperature and carbon content. Understanding these boundaries is crucial for predicting the microstructure and properties of iron-carbon alloys.

**1. Solubility Limits:** The Fe-C diagram illustrates the maximum solubility of carbon in different phases of iron. For example, at room temperature, pure iron (alpha-iron or ferrite) can dissolve only a small amount of carbon, up to about 0.008%. As temperature increases, the solubility of carbon in iron also increases, reaching its peak at the eutectic composition, beyond which excess carbon precipitates out as cementite ($Fe_3C$).

**2. Phase Boundaries:** The phase boundaries separate regions of different phase compositions and structures. For instance, the boundary between ferrite and austenite marks the transition from a body-centered cubic (BCC) structure to a face-centered cubic (FCC) structure as temperature increases. Similarly, the eutectoid boundary separates the region where austenite transforms into a mixture of ferrite and cementite upon cooling.

**3. Eutectic Reaction:** At the eutectic composition (around 4.3% carbon), there is a eutectic reaction where liquid phase transforms directly into two solid phases: austenite and cementite. This reaction occurs at a specific temperature known as the eutectic temperature, which is around 1147°C in the Fe-C system.

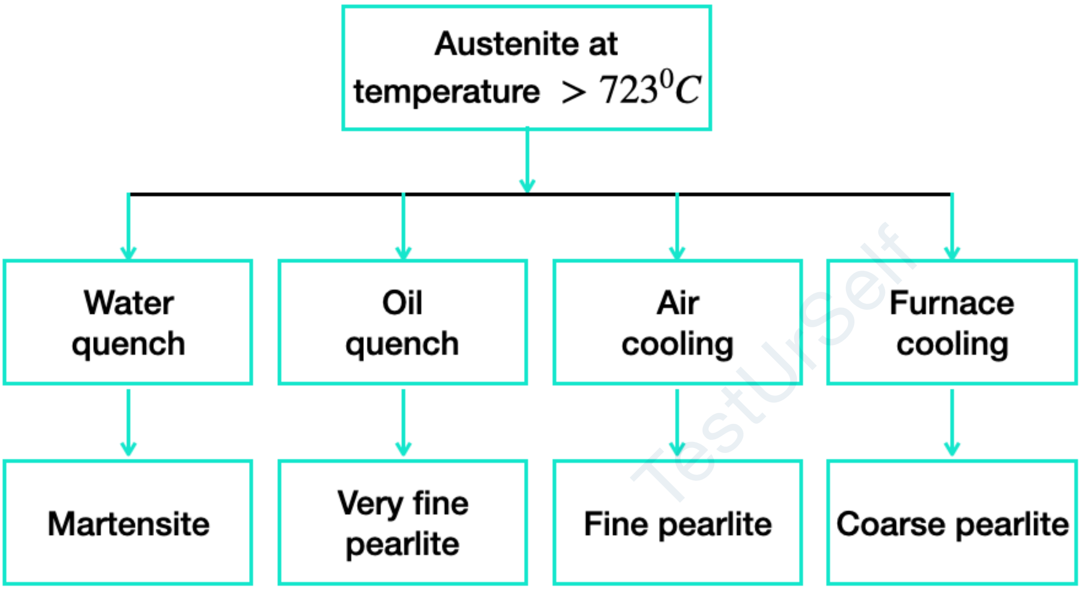
**4. Peritectic Reaction:** The peritectic reaction involves the transformation of a solid phase and a liquid phase into another solid phase. In the Fe-C diagram, this occurs when delta-ferrite transforms into austenite upon heating at a specific temperature and composition.

**5. Critical Points:** Critical points, such as the A1 (Ac1) and A3 (Ac3) temperatures, mark important temperatures at which phase transformations occur. Ac1 represents the temperature at which austenite begins to form upon heating, while Ac3 marks the completion of the transformation of ferrite into austenite.

Understanding these boundaries and critical points allows engineers and metallurgists to design and control the microstructure and properties of iron-carbon alloys for various applications, ranging from structural steels to cast irons.

# Microstructures in Fe-C diagram:

In the Iron-Iron Carbide Phase Diagram, the microstructures of pearlite, bainite, and martensite play significant roles in determining the properties of steel and cast iron alloys.




**1. Pearlite:**

- Pearlite forms when austenite (FCC phase) transforms into a mixture of ferrite (alpha-iron) and cementite ($Fe_3C$) upon cooling.
- It appears as lamellar structures under a microscope, comprising alternating layers of ferrite and cementite.
- Pearlite is relatively soft and ductile compared to other microstructures like martensite, making it suitable for applications requiring toughness and machinability.
- It is commonly found in low to medium carbon steels, where the carbon content ranges between 0.2% to 0.8%.

**2. Bainite:**

- Bainite forms when austenite is transformed at relatively lower temperatures compared to pearlite formation but higher than martensite transformation.

- It consists of fine, needle-like ferrite crystals embedded in a matrix of carbon-enriched austenite.
- The transformation of austenite to bainite is slower than the transformation to martensite, resulting in reduced distortion and lower hardness compared to martensite.
- Bainite offers a good balance of strength, toughness, and ductility, making it suitable for applications where high strength and toughness are required, such as gears and automotive components.

**3. Martensite:**
- Martensite forms when austenite is rapidly cooled (quenched) to room temperature, bypassing the equilibrium transformation phases.
- It has a highly distorted, tetragonal crystal structure due to the rapid cooling, resulting in high hardness and strength.
- Martensite is characterized by a needle-like or lath-like microstructure and is extremely hard and brittle.
- It is commonly found in high carbon steels and is used in applications where hardness, wear resistance, and strength are critical, such as cutting tools, springs, and knife blades.
- Martensite can be tempered to reduce its brittleness and improve toughness while retaining high strength.

Understanding the formation and characteristics of these microstructures in the Iron-Iron Carbide Phase Diagram is essential for controlling the properties of steel and cast iron alloys to meet specific engineering requirements.

# Phase Transformations in Fe-C diagram:

In the Iron-Carbon (Fe-C) phase diagram, several phase transformation reactions occur as a function of temperature and carbon content. These reactions dictate the microstructure and properties of iron-carbon alloys. Here are the key phase transformation reactions:

**1. Solidification (Melting):**
- At temperatures below the melting point of iron (1539°C), the Fe-C diagram represents the solid phases of iron and iron carbide.
- Upon cooling, solidification occurs as liquid iron transforms into solid phases according to the phase boundaries and compositions outlined in the diagram.

**2. Eutectic Reaction:**

- The eutectic reaction occurs at the eutectic composition of approximately 4.3% carbon and the eutectic temperature of around 1147°C.
- During this reaction, the liquid phase transforms directly into two solid phases: austenite (γ-phase) and cementite (iron carbide, $Fe_3C$).
- The eutectic microstructure consists of alternating layers of austenite and cementite, known as pearlite.

**3. Eutectoid Reaction:**

- The eutectoid reaction takes place at a eutectoid composition of around 0.8% carbon and a eutectoid temperature of about 727°C.
- During cooling, austenite transforms into a mixture of ferrite (α-phase) and cementite through this reaction.
- The resulting microstructure is known as pearlite, characterized by lamellar layers of ferrite and cementite.

**4. Peritectic Reaction:**

- The peritectic reaction occurs when δ-ferrite (delta-ferrite) transforms into austenite upon heating at a specific temperature and composition.
- This reaction involves the dissolution of δ-ferrite into the liquid phase, followed by the formation of austenite.
- The peritectic reaction typically occurs at temperatures above the eutectoid temperature but below the melting point of iron.

**5. Solid-Solid Phase Transformations:**

- Other solid-solid phase transformations include the formation of bainite and martensite.
- Bainite forms when austenite transforms into a mixture of ferrite and cementite at relatively lower temperatures compared to pearlite formation.
- Martensite forms when austenite is rapidly quenched to room temperature, bypassing equilibrium phase transformations. It is characterized by a highly distorted, metastable structure with high hardness and brittleness.

Understanding these phase transformation reactions in the Fe-C diagram is crucial for controlling the microstructure and properties of iron-carbon alloys for various industrial applications.

# Types of Steels and Cast Irons in Fe-C diagram:

*Iron-Carbon (Fe-C) phase diagram is pivotal for classifying different types of steels and cast irons, primarily based on their carbon content and the resultant microstructures. Here's a simplified classification as observed in the Fe-C diagram:*

**1. Hypo-Eutectoid Steel:** Contains carbon content less than the eutectoid composition (0.8%). After the eutectoid transformation, the resulting microstructure contains mostly ferrite with pearlite. These steels are often heat-treated to improve their strength, toughness, and wear resistance. Commonly used in automotive components, shafts, and machinery parts.

**2. Hyper Eutectoid Steel:** Hypereutectoid steels have a carbon content above the eutectoid composition (0.8% carbon) and typically contain pearlite and cementite microstructures.

Steels are iron-carbon alloys with a carbon content generally less than 2%. They are divided into several categories based on their carbon content and treatment processes:

**1. Low Carbon Steel (Mild Steel):** Contains up to 0.3% carbon. It is ductile, malleable, and has low tensile strength. Used in automobile body components, pipelines, and structural steel.

**2. Medium Carbon Steel:** Contains 0.3% to 0.6% carbon. Offers a better balance between strength, ductility, and toughness. Used in gears, rails, and structural steel where higher strength is required.

**3. High Carbon Steel:** Contains 0.6% to 1.2% carbon. It is harder and stronger than low and medium carbon steels but less ductile. Used in tools, knives, and spring steel.

**4. Alloy Steels: T**hese steels contain other alloying elements like chromium, nickel, and molybdenum in addition to carbon. The composition and treatment of these steels can provide enhanced properties like increased strength, hardness, or corrosion resistance.

**Cast irons** are iron-carbon alloys with a carbon content greater than 2%, and they manifest in several forms depending on their microstructure:

**1. Gray Cast Iron:** Contains 2.5% to 4% carbon. Its carbon content is primarily in the form of graphite flakes, giving it its gray appearance when fractured. It is used for engine blocks, pipes, and machine bases due to its good machinability and vibration damping properties.

**2. Ductile (Nodular) Cast Iron:** Also contains 2.5% to 4% carbon but with the carbon forming spherical nodules rather than flakes. This provides better ductility and tensile strength than gray cast iron. Used in applications requiring higher strength and toughness, like automotive components and heavy-duty gears.

**3. White Cast Iron:** Contains 1.8% to 3.6% carbon with carbon in the form of cementite ($Fe_3C$). It is hard and brittle due to its microstructure. Used in wear-resistant applications such as mill liners and industrial crushers.

**4. Malleable Cast Iron:** Produced by heat-treating white cast iron to convert cementite into graphite in the form of temper carbon. This process enhances its ductility and strength. Used for parts requiring high strength and toughness like railway equipment and heavy-duty gears.

**5. Compacted Graphite Iron (CGI):** Has a carbon content between that of gray and ductile iron, with graphite in short, compacted shapes. Offers better strength, stiffness, and thermal conductivity than gray cast iron, used in high-performance applications like engine blocks and cylinder heads.

The classification and understanding of these steels and cast irons are essential for materials engineers to select the appropriate material for specific applications, taking advantage of their unique properties as dictated by their microstructure and composition in the Fe-C phase diagram.

## Significance of Fe-C diagram:

Iron-Carbon (Fe-C) phase diagram holds significant importance in metallurgy and materials science for several reasons:

**1. Understanding Phase Transformations:** The Fe-C phase diagram provides valuable insights into the various phase transformations that occur in iron-carbon alloys as a function of temperature and composition. This understanding is crucial for controlling the microstructure and properties of steels and cast irons during processing and heat treatment.

**2. Microstructure Design:** By interpreting the phase diagram, engineers and metallurgists can design specific microstructures tailored to achieve desired mechanical properties. For example, controlling the cooling rate during solidification can result in different microstructures such as pearlite, bainite, or martensite, each offering unique combinations of strength, hardness, and toughness.

**3. Selection of Alloys:** The phase diagram aids in selecting appropriate alloy compositions for different applications. By considering the desired mechanical, thermal, and corrosion resistance properties, engineers can choose the most suitable alloy composition based on its phase stability and transformation behavior.

**4. Heat Treatment Optimization:** Heat treatment processes such as annealing, quenching, and tempering rely on the phase diagram to determine the optimal processing parameters. Understanding the phase transformations allows for precise control over the microstructure evolution, resulting in enhanced material properties and performance.

**5. Quality Control and Failure Analysis:** The phase diagram serves as a reference tool for quality control in manufacturing processes. It enables the identification of potential phase transformations and microstructural changes that may affect the integrity and performance of the final product. Additionally, in failure analysis investigations, knowledge of the phase diagram aids in understanding the root causes of material failures and devising corrective measures.

Overall, the Fe-C phase diagram is a fundamental tool for the design, processing, and characterization of iron-carbon alloys, playing a pivotal role in the development of advanced materials for various industrial applications, including automotive, aerospace, construction, and manufacturing.

# Questions on Fe-C diagram:

**Q.1: The reaction in which a liquid phase transform into two different solid phases is called**

A. Eutectoid reaction
B. Peritectic reaction
C. Eutectic reaction
D. Peritectoid reaction

**Ans: C**

The reaction in which a liquid phase transforms into two different solid phases is called a Eutectic reaction (Option C). Here are the details for each reaction:

**- Eutectoid reaction (Option A):** This is a three-phase reaction in which, upon cooling, one solid phase transforms into two other solid phases at the same time. An example is the transformation of austenite into ferrite and cementite in the iron-carbon system.

**- Peritectic reaction (Option B):** This reaction involves a liquid phase and a solid phase that together form a second solid phase at a specific temperature and composition. The reaction can be represented as `Liquid + Solid1 ⇌ Solid2.

**- Eutectic reaction (Option C):** This is a three-phase reaction in which, upon cooling, a liquid transforms into two solid phases at the same time. The eutectic reaction is expressed as `Liquid ⇌ Solid1 + Solid2.

**- Peritectoid reaction (Option D):** This is a solid-state reaction in which two solid phases react to form a single, new solid phase. The reaction can be represented as `Solid1 + Solid2 ⇌ Solid3.

**Q.2: Which of the following phase of steel is NOT present in Iron-Carbon phase diagram?**

A. Ferrite

B. Cementite
C. Austenite
D. Martensite

**Ans: D**

The phase of steel that is NOT present in the Iron-Carbon phase diagram is Martensite (Option D). Here are the details for each phase:

**- Ferrite (Option A):** Ferrite, or alpha-iron, is a phase of steel that exists below temperatures of 910°C for low concentrations of carbon in iron. It is the primary phase of low-carbon or mild steel and most cast irons at room temperature.

**- Cementite (Option B):** Cementite, or iron carbide ($Fe_3C$), is an extremely hard intermetallic compound of iron and carbon. It is present in all steel containing more than 0.8% carbon.

**- Austenite (Option C):** Austenite, also known as gamma-phase iron (γ-Fe), is a non-magnetic face-centered cubic structure phase of iron. Austenite in iron-carbon alloys is generally only present above the critical eutectoid temperature (723°C), and below 1493°C, depending on carbon content.

**- Martensite (Option D):** Martensite is a hard, brittle phase of steel that is the chief constituent of hardened steel. Unlike the other phases, martensite is not a phase associated with thermal equilibrium and thus, it does not appear on the iron-carbon equilibrium phase diagram.

**Q.3: The eutectic percentage of carbon in iron is**

A. $0.025\ \%$
B. $0.15\ \%$
C. $2.03\ \%$
D. $4.33\ \%$

**Ans: D**

Here's a detailed explanation of the three important transformations of the iron-carbon equilibrium diagram:

**1. Eutectoid Reaction:**

- This reaction occurs at a temperature of $723^{\circ}\mathrm{C}$ and a carbon composition of $0.8\,\%$.
- The reaction involves the transformation of austenite ($\gamma$) into a mixture of ferrite (alpha-iron, $\alpha$) and cementite (iron carbide, $\mathrm{Fe_3C}$).
- The reaction equation is:

$$\gamma(\mathrm{S}) \rightleftarrows \alpha(\mathrm{S}) + \mathrm{Fe_3C(S)}$$

- Here, one solid phase (austenite) is converted into two solid phases (ferrite and cementite).

**2. Eutectic Reaction:**

- This reaction occurs at a temperature of $1147^{\circ}\mathrm{C}$ and a carbon composition of $4.3\,\%$.
- The reaction involves the transformation of liquid iron (L) into a mixture of austenite (gamma, $\gamma$) and cementite ($\mathrm{Fe_3C}$).
- The reaction equation is:

$$\mathrm{L(S)} \rightleftarrows \gamma(\mathrm{S}) + \mathrm{Fe_3C(S)}$$

- Here, one liquid phase is converted into two solid phases.

**3. Peritectic Reaction:**

- This reaction occurs at a temperature of $1497^{\circ}\mathrm{C}$ and a carbon composition of $0.09\,\%$.
- The reaction involves the transformation of delta-ferrite ($\delta$-iron) and liquid iron (L) into austenite ($\gamma$).
- The reaction equation is:

$$\delta(\mathrm{S}) + \mathrm{L(S)} \rightleftarrows \gamma(\mathrm{S})$$

- Here, one solid phase (delta-ferrite) and one liquid phase are converted into another solid phase (austenite).

These three transformations are crucial in understanding the phase changes and microstructural evolution that occur in iron-carbon alloys at different temperatures and carbon compositions. They play a significant role in determining the properties and behavior of steels and cast irons under various processing and heat treatment conditions.

**Q.4: Hyper eutectoid steels have structure of-**

A. Pearlite alone
B. Phases of ferrite and pearlite
C. Phases of cementite and pearlite
D. Phases of ferrite and cementite

**Ans: C**

The correct answer is C. Phases of cementite and pearlite.

Hyper eutectoid steels are those that contain more than 0.8% carbon. According to the Iron-Carbon phase diagram, when these steels are cooled, the austenite phase transforms into pearlite (which is a mixture of alternate layers of ferrite and cementite) and cementite.

Here's a detailed explanation:

- **Eutectoid Steel:** This is steel that contains 0.8% carbon. It is a specific composition where, upon cooling austenite to lower than 723°C (the eutectoid reaction), the austenite turns into pearlite.

- **Hypo-eutectoid Steel:** Steel with less than 0.8% carbon is known as hypo-eutectoid steel. Its structure is a mixture of pearlite and ferrite.

- **Hyper-eutectoid Steel:** Steel with more than 0.8% carbon is known as hyper-eutectoid steel. Its structure is a mixture of pearlite and cementite.

It is a certain composition where, upon cooling austenite to lower than $723^{\circ}C$ (eutectoid reaction), the austenite turns into pearlite (alternate layers of ferrite and cementite).

Eutectoid reaction is given by

$$\gamma \rightleftarrows \alpha + Fe_3C$$

The eutectoid reaction can be observed in the Iron-carbon phase diagram.

So, in hyper-eutectoid steels, the excess carbon precipitates out as cementite. This results in a microstructure of pearlite (which itself is a layered structure of ferrite and cementite) interspersed with additional cementite.